Optimal Sizing of Combined PV- Energy Storage for a Grid-connected Residential Building

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Abstract

In this paper, load profile and operational goal are used to find optimal sizing of combined PV-energy storage for a future grid-connected residential building. As part of this approach, five operational goals are introduced and the annual cost for each operation goal has been assessed. Finally, the optimal sizing for combined PV-energy storage has been determined, using direct search method. In addition, sensitivity of the annual cost to different parameters has been analyzed.

Keywords

PV; Energy Storage; Operational Goal; LV Network Constraints

Introduction

Future networks will include widespread penetration of Small-Scale Generators like PVs, wind turbines and fuel cells in residential area. PV sources increasingly contribute to the total renewable energy in LV network [1]. There are two types of PV system in LV network, standalone and grid-connected, in the first of which used for remote area, the aim is to balance the load and generation to prevent loss of load in each time step. Therefore, the optimization algorithms are used to minimize the cost and the loss of load.

However, for the grid-connected type, the main problem is power quality issues. The high penetration of grid-connected PVs may reverse the power flow in the network and introduce new technical challenges for the system. These issues include voltage tripping, voltage imbalance, harmonic and reverse power flow.

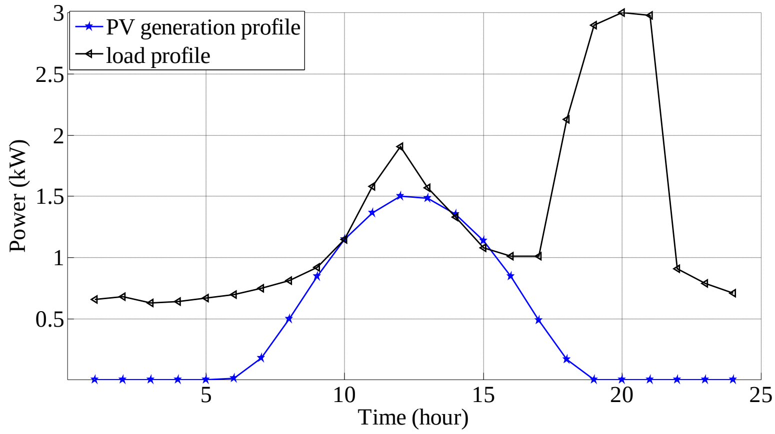
To deal with technical challenges of grid-connected PV, different strategies have been addressed in literatures. The first approach is to curtail PVs output power in critical condition. This approach is attractive, but contradicts the maximum use of renewable energy. The second way is to export power to neighboring grids. However, this may happen while the neighboring grid has the same balancing problem. The third approach is to use energy storage unit in addition to PV in each residential house to store the surplus power in low load durations, and use the energy when it is needed in peak load times. The usage of storage can bring advantages for both utility and customer. In customer side, it would be beneficial to store the electricity in low price operation periods (light load times) and use it in high price periods (peak demand). For utility, the distributed storage units can minimize the negative impacts of PV on LV network. It also can shave the peak demand of feeder, which is attractive for utilities. As a result, the introduction of small scale storage is a promising concept for future grid-connected residential building. Consequently, the sizing of PV and energy storage becomes an important economical issue which has been recognized in this paper. Load profile and LV network constrains in terms of operational modes would affect the sizing issues. With respect to the policies used around the world to deal with the network constrains, five types of operational goals that can be anticipated for future residential buildings are introduced in section 2. Considering the operational goals and the building load profiles, a strategy based on an annual cost analysis is used for optimal sizing of combined PV-energy storage, in this paper. The rest of the paper is organized as follow. The effective parameters in sizing of combined PV-energy storage have been introduced in section 2. Section 3 describes the model to find the optimal sizing of PV and storage. Finally, as a case study, a typical grid-connected residential building has been studied in section 4 to find out the optimal size of its PV and energy storage.

Effective Parameters in Sizing of Combined PV-Energy Storage

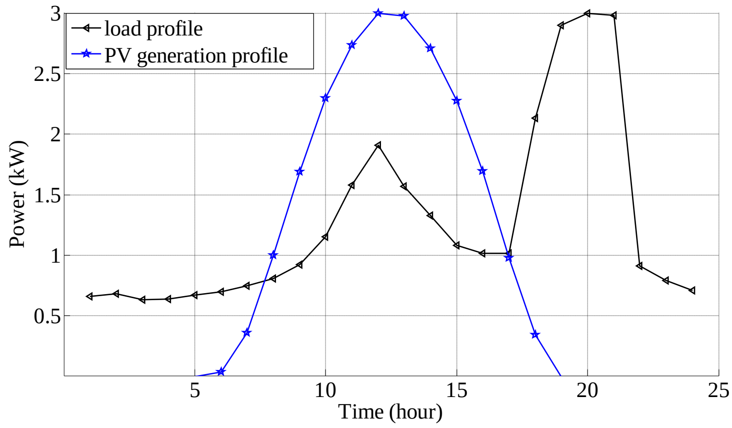
There are two main parameters that should be considered in optimal sizing of combined PV-energy storage for a grid-connected residential building which have been explained as follow.

Load Profile

There are many large-scale projects around the world for smart-metering systems to make the network more intelligent. The frontrunner countries are Italy and Sweden (nearly 100% implemented at the end of 2011). The primary role of smart-metering system is to provide load data which can be used to generate accurate customer load profile. Load profile can make significant effect on PV-energy storage sizing decision. In the followings, examples are illustrated to show this effect.



(a) 1.5 kW PV



(b) 3 kW PV

FIG. 1 LOAD AND PV GENERATION PROFILES; FOR (a) 1.5 kW, (b) 3 kW PVs

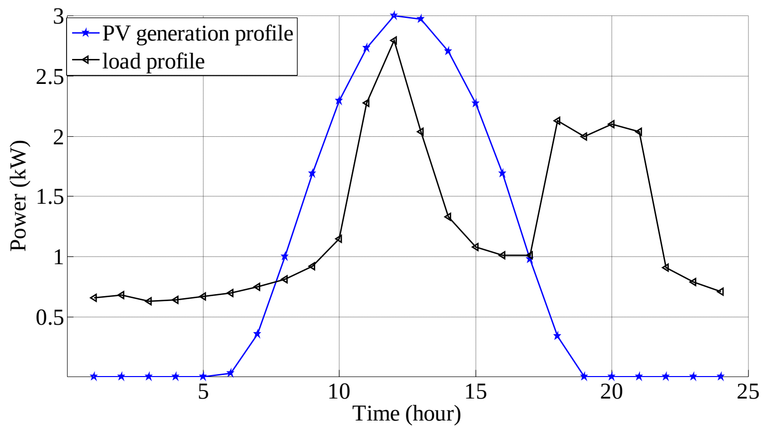


FIG. 2 SHIFTED LOAD AND PV GENERATION PROFILES

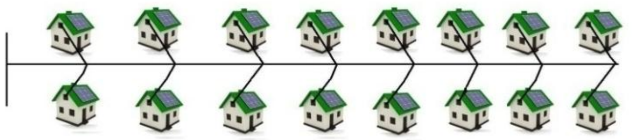
Consider the cases where two PV systems (1.5 and 3 kW) are the candidates to be used in a residential building with average consumption of 30.5 kWh per day. It is assumed that the average generation and load profiles of this building are as shown in Fig. 1. In the case of 1.5 kW PV, the generation is always lower than the consumption and no surplus power is produced. However, in the case of 3 kW PV, it can be seen that there is a considerable surplus of energy in low load condition (during the day). If this surplus energy is injected to the network, it may cause power quality issues, such as voltage violation. Under this condition, it is assumed that customer is not allowed to inject power into the grid. As a result, the first plan (1.5 kW PV) can fulfill the goal of no injection power to the grid. However, for 3 kW PV, a storage unit is needed to store the surplus energy in low load period. A simple calculation suggests the minimum sizing for this storage required to be 10 kWh. However, if the owner has the ability to shift a percentage of the consumption to the low load period in the middle of the day, then the sizing of storage could be decreased. For example, customer can shift the deferrable load to low load period as shown in Fig. 2. In this case, only 7 kWh of storage is needed for the surplus power. As a result, it is concluded that the load profile of customer is an important parameter in sizing of the PV and storage.

Operational Goals

Case 1: 25% penetration

Case 2: 50% penetration

Case 3: 75% penetration



Case 4: 100% penetration

FIG. 3 RESIDENTIAL PV DEVELOPMENT

Fig. 3 illustrates a residential feeder with low to high density penetration of grid-connected PV, exemplifying the progression into the future. Cases 1 and 2 can represent some of the current situations around the world, where PVs can inject their surplus power into the network without any limitation. For these two cases, no power quality constraints are violated. However, by increasing the penetration level of PVs (cases 3 and 4 in Fig. 3), in low load period, PVs generate their maximum power and this results in power quality issues along the feeder, in low load period. As a result, some limitations should be applied to the residential buildings to prevent the issues. Considering the building location in the feeder, it has different effects on the power quality of the network. For example, the ones close to upstream network would have less effect on grid voltage fluctuation versus those at the end of the feeder. Therefore, different limitations should be applied to the buildings considering their locations.

Considering the foregoing observations, five different operational goals for a grid-connected residential building can be anticipated, as follows:

1) Zero Power Export (Self-Consumption)

The first operational goal for a residential building is self-consumption scenario (zero export power to the grid). For instance, since 2009, domestic storage units for self-consumption of PV energy have been encouraged in Germany. In this policy, the owner of PV (up to 30 kW) receives an allowance of 0.25 Euro/kWh for the consumption of the generated power. As a result, it is attractive to store the surplus power instead of sending into the grid and use it back later in peak demand duration.

This policy avoids the negative impact of power injection into grid and shifts the generation to the peak demand time. This mode of operation is also advantageous for peak load shaving. Therefore, this operation strategy for grid-connected building can help utilities for power quality improvement and peak load shaving. Considering Fig. 4, this operational goal can mathematically be expressed as follow:

$$P_{grid,h}^{\mathrm{exp}ort} = 0 \quad and \quad P_{grid,h}^{import} \geq 0$$
$$for \quad h = 1, 2, ..., 8760$$

where, $P_{grid,h}^{\mathrm{exp}ort}$ is the building exported power to the grid at hour h; $P_{grid,h}^{import}$ is the buiding imported power from the grid at hour h

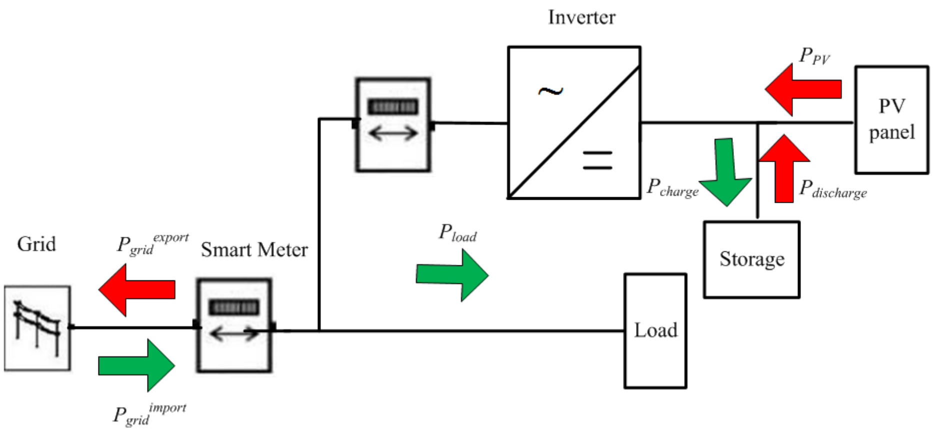


FIG. 4 TYPICAL TOPOLOGY OF FUTURE RENEWABLE ENERGY SYSTEM IN A GRID-CONNECTED RESIDENTIAL BUILDING

2) *Zero Power Import*

If the total generated power by a small scale generator is always more than the building consumption and it is allowed to inject the power into grid, the building can be considered for zero power import mode of operation. As a result, such a residential building only exports the power to the grid and do not import any power from the grid. This is mathematically shown as:

$$P_{grid,h}^{export} \geq 0 \quad and \quad P_{grid,h}^{import} = 0$$
$$for \quad h = 1, 2, ..., 8760$$

Considering the intermittence characteristic of PV, this goal cannot be fulfilled by a PV and a big storage is needed. Therefore, this operational goal is not analyzed in this paper.

3) *Maximum Power Export*

The third possible goal for a building is to have a limited right to inject power into the grid. It is proposed to prevent LV network constraints violation by limiting the maximum injected power of each customer to $P_{\max}^{export}$. The maximum amount of injected power, in this case, can be determined while network limit is not violated. This limitation can be varying for different building considering the location of building in the grid. The constraint for this mode can be expressed as follow:

$$P_{grid,h}^{export} \leq P_{\max}^{export} \quad and \quad P_{grid,h}^{import} \geq 0$$
$$for \quad h = 1, 2, ..., 8760$$

4) *Maximum Power Import*

This operational goal aims to shave the peak load of a network and limit the non-renewable electricity consumption. For instance, in UK, there is a tax named CCL (Climate Change Levy) for non-domestic sectors on the use of non-renewable electricity. The rate of tax is 0.43 p/kWh and it is aimed to reduce 2.5 million tons of carbon dioxide each year [23].

Similar policy can be applied to a residential area where each residential house that consumes more than a specified power ($P_{\max}^{import}$) can be penalized by a levy for extra consumption. These constraints are given in as follow:

$$P_{grid,h}^{export} \geq 0 \quad and \quad P_{grid,h}^{import} \leq P_{\max}^{import}$$
$$for \quad h = 1, 2, ..., 8760$$

5) *Maximum Power Import and Export*

Finally, the last possible operational goal for a residential house could be the mix of operational goals of 3 and 4. This mode of operation has the advantage of both operational goals. The constraint for this operational goal is given as follow:

$$P_{grid,h}^{export} \leq P_{\max}^{export} \quad and \quad P_{grid,h}^{import} \leq P_{\max}^{import}$$
$$for \quad h = 1, 2, ..., 8760$$

The goal for each case may give different cost/benefit to customer and utility, as described earlier. As a result, it can be said that the sizing of both PV and storage need to be carefully determined, considering these operational goals.
In the following section, the detail of combined PV-energy storage sizing approach for a Grid-connected residential building has been shown. The study aims to determine this case in consideration with different operational goals. Annual cash flow is used to compare different sizing plan.

Describtion of the Model

Fig. 5 shows a flowchart illustrating the structure of the model which has been used in this paper for sizing of combined PV- energy storage for a residential building. The hourly climate data are used to make the generation profile for different PV capacity. In addition, the hourly electricity load profile can be determined, considering the customer consumption characteristics and appliances in the building. The sizing of storage is determined considering the generation and load profiles with respect to a predetermined operational goal. The following assumptions are used in sizing the storage:

- The storage is only charged with PV generation,
- Every day at 6a.m., the storage needs to be in initial charging condition (20%),
- There is no injection of power into grid, between 6 pm – 6 am,
- The maximum level of power import is exclusive to nights (7 Pm- 12 Pm) when there is peak load condition. As a result, if the imported power violates this rule during a day, the customer will not be charged for CCL tax.

After a plan (PV size and storage capacity) is determined, the details are fed into the optimization algorithm to find the annual cost of the plan. In addition, PV and storage cost and technical data including efficiency, capital cost, maintenance cost and lifetime are fed into the optimization algorithm which requires the rates of electricity tariff, interest rate and government policies (subsidies, self-consumption incentive rate, feed-in-tariff rate and CCL rate). Once an operational goal is provided, the algorithm finds the annual cost for different plans and determines the optimal plan.

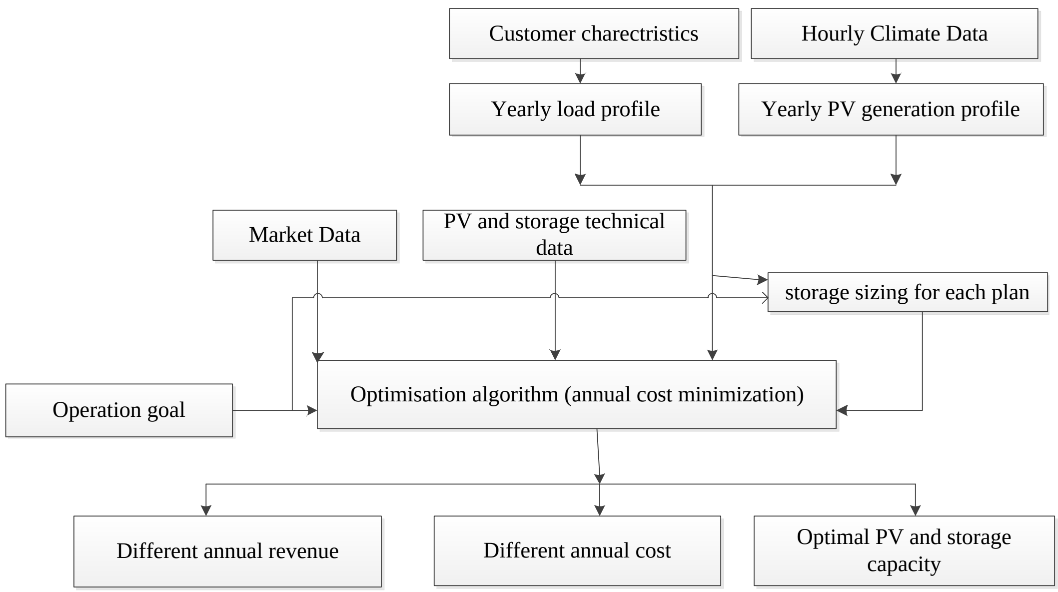


FIG. 5 FLOW CHART FOR COMBINED PV- ENERGY STORAGE SIZING ALGORITHM

Objective Function

The objective functions, considering the type of operational goal of the building, can be written as follow:

Self-consumption

$$\min\{ C_{total} = CP_{inv} + CP_{main} + CP_{elec} - CR_{self-consumption} \} \quad (1)$$

Zero power import

$$\min\{ C_{total} = CP_{inv} + CP_{main} - CR_{feed-in-tarrif} \} \quad (2)$$

Maximum power export

$$\min\{ C_{total} = CP_{inv} + CP_{main} + CP_{elec} - CR_{feed-in-tariff} \} \quad (3)$$

Maximum power import

$$\min\{ C_{total} = CP_{inv} + CP_{main} + CP_{elec} + CP_{CCL} - CR_{feed-in-tariff} \} \quad (4)$$

Maximum power import and export

$$\min\{ C_{total} = CP_{inv} + CP_{main} + CP_{elec} + CP_{CCL} - CR_{feed-in-tariff} \} \quad (5)$$

where C_{total} is the total annual cost of system,
CP_{inv} is the PV and storage investment cost,
CP_{main} is the maintenance cost of the system,
CP_{elec} is the building annual electricity cost,
CP_{CCL} is the annual CCL cost,
$CR_{self-consumption}$ is the income from self-consumption policy,
$CR_{feed-in-tariff}$ is the income from selling the electricity to the grid.

The annualized investment cost (CP_{inv}), considering the

incentive policy of the government, can be determined as follow:

$$CP_{inv} = (C_{PV}).(1 - Incrate_{PV}).P_{PV} + C_{storage}.(1 - Incrate_{storage}).E_{storage} \quad (6)$$

where C_{PV} is the annualized investment cost of PV,
$C_{storage}$ is the annualized investment cost of storage,
P_{PV} is the power rating of PV,
$E_{storage}$ *is* the energy rating of storage,
$Incrate_{PV}$ is the installation incentive rate for PV (the part of PV investment cost paid by government incentive),
$Incrate_{storage}$ is the installation incentive rate for storage (the part of storage investment cost paid by government incentive).

The maintenance cost (CP_{main}) of the system is the sum of maintenance cost of both PV and storage which is linearly proportional to the power of PV and the charged or discharged energy of storage in each hour (this cost has not been considered in this paper).

The annual electricity cost of the building (CP_{elec}) can be determined by the following equation:

$$CP_{ele} = \sum_{h=1}^{8760} price_h . P_{grid,h}^{import} \quad (7)$$

where $Price_h$ is the electricity price at hour h,

The annual CCL cost (CP_{CCL}), while the maximum power import of the building is limited; can be determined using equation (8).

$$CP_{CCL} = \sum_{h=1}^{8760} rate_{CCL}.(P_{grid,h}^{import} - P_{\max}^{import}) \quad (8)$$

where $rate_{CCL}$ is the CCL rate for more power consumption.

Finally, the income coming from self-consumption ($CR_{self\text{-}consumption}$) and feed-in-tariff ($CR_{feed\text{-}in\text{-}tariff}$) can be obtained with equations (9) and (10):

$$CR_{self-consumption} = \sum_{h=1}^{8760} rate_{self-consumption}.P_{self-consumption,h} \quad (9)$$

$$CR_{feed-in-tariff} = \sum_{h=1}^{8760} rate_{feed-in-tariff}.P_{grid,h}^{export} \quad (10)$$

where $rate_{self\text{-}consumption}$ is the self-consumption incentive rate, $rate_{feed\text{-}in\text{-}tariff}$ is the feed-in-tariff rate.

Equality and Inequality Constraints

The balance between supply and demand in each time step can be achieved by equation (11):

$$P_{PV,h} + P_{storage,h} + P_{grid,h}^{import} = P_{load,h} \quad (11)$$

Considering the physical and environmental limitations, the rating of PV and storage is limited as shown in equations (12) and (13):

$$P_{PV} \le P_{PV}^{\max} \quad (12)$$

$$E_{storage} \le E_{storage}^{\max} \quad (13)$$

In addition, the following constraints for each operational goal should be considered in the optimization algorithm:

Zero power export (Self-consumption)

$$P_{grid,h}^{export} = 0, P_{grid,h}^{import} \ge 0 \quad (14)$$

Zero power import

$$P_{grid,h}^{export} \ge 0, P_{grid,h}^{import} = 0 \quad (15)$$

Maximum power export

$$P_{grid,h}^{export} \le P_{\max}^{export}, P_{grid,h}^{import} \ge 0 \quad (16)$$

Maximum power import

$$P_{grid,h}^{export} \ge 0, P_{grid,h}^{import} \le P_{\max}^{import} \quad (17)$$

Maximum power import and export

$$P_{grid,h}^{export} \le P_{\max}^{export}, P_{grid,h}^{import} \le P_{\max}^{import} \quad (18)$$

Case Study

In this section, a grid-connected residential building with annual hourly load profile of Fig. 6 is used as a case study to find the optimal PV and storage sizing for different operational goals. The type and details of PV panel is shown in Table I. In addition, the annual hourly generation profile of this panel is given in Fig. 7. Homer software has been used to estimate the amount of load and generation of the building for each hour during a year. Due to installation space limitation, the maximum allowable PV rating is considered to be 4.8 kW for the building. The direct search optimization method has been used to establish an optimal plan for each operational goal. Table II shows the component cost and economic factors which are used in the following case studies to determine the cash flow for each plan.

TABLE I PV PANEL PARAMETERS

Maximum power	*100 w*
Efficiency	*12 %*
Capital cost	*400 $*
Life time	*20 years*

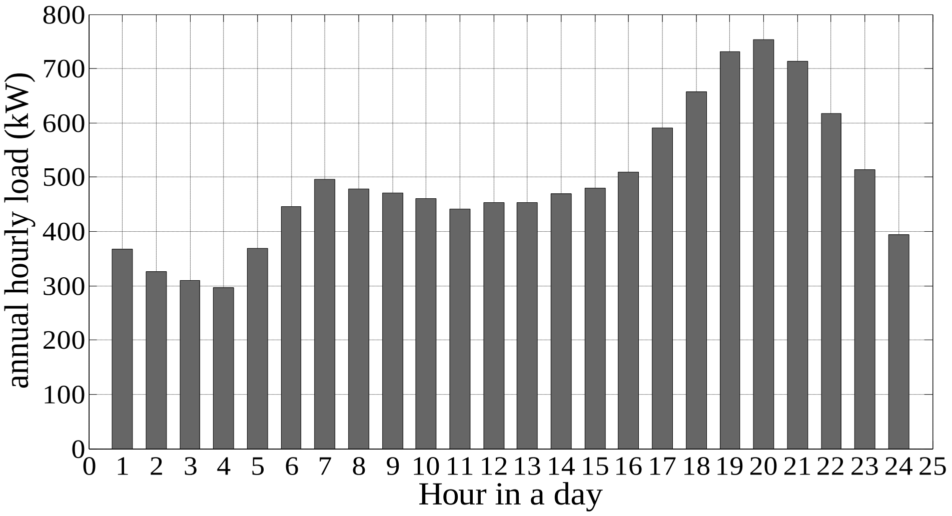


FIG. 6 ANNUAL CUSTOMER LOAD PROFILE

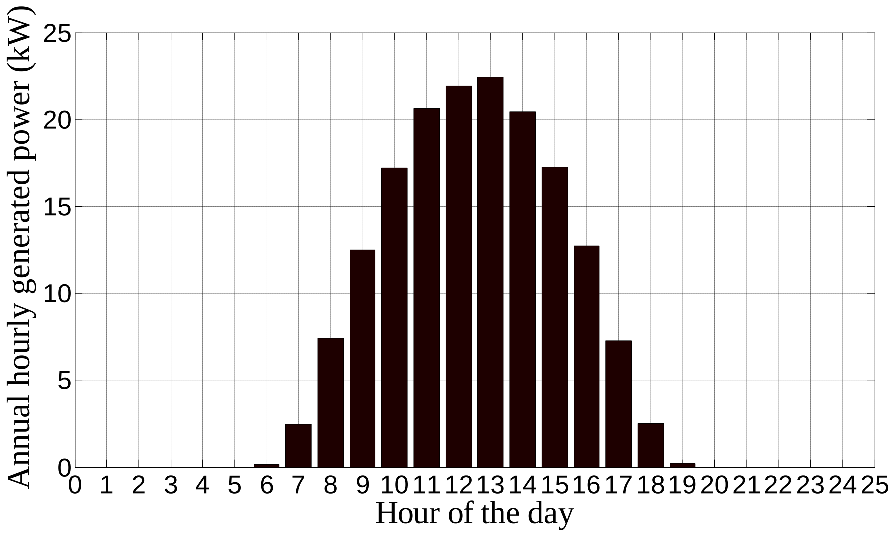


FIG. 7 ANNUAL GENERATED POWER BY THE PV PANEL

TABLE II LIST OF THE COMPONENT COSTS AND THE ECONOMIC FACTORS

Storage	
Average cost	*400 $/kWh*
Life cycle	*3 years*
Charge efficiency	*100%*
Discharge efficiency	*80%*
Initial state of charge	*20%*
PE converter	
Average cost	500 $/kW
Life cycle	10 years
Economic parameters	
Off-peak electricity price (1am-6am)	0.2 $/kWh
Semi-peak electricity price (7am-5pm)	0.3 $/kWh
Peak electricity price (6pm-12pm)	0.5 $/kWh
Feed-in-tariff rate	0.40 $/kWh
Self-consumption incentive rate	0.23 $/kWh
CCL rate	0.40 $/kWh
Installation Incentive rate for PV	0.4
Installation Incentive rate for storage	0.4
Interest rate	0.06

Zero Power Export (Self-Consumption)

TABLE III OPTIMAL PLAN (ZERO POWER EXPORT)

P_{PV} (kW)	2.3
$E_{storage}$(kWh)	6.7
CP_{inv} ($)	1209.1
CP_{elec} ($)	2885.5
$CR_{feed\text{-}in\text{-}tariff}$ ($)	0
$CR_{self\text{-}consumption}$ ($)	849.54
CP_{CCL}($)	0
C_{total} ($)	3245.1

In this operational goal, it is assumed that the building cannot inject any power into the grid. Table III shows the optimal sizing of the combined PV- energy storage for the building to fulfill this operational goal, with minimum annual cost. For this operational goal, the individual and the total annual costs as a function of PV capacity is shown in Fig. 8. It can be seen when the PV capacity increases, the investment cost and the self-

consumption income increase as well, but the cost of electricity decreases. With PV rating equal to 2.3 kW, the total annual cost is minimized.

Fig. 9 shows the change in different investment cost versus change in PV capacity. It can be seen when the PV capacity increased, the investment cost for storage increased dramatically. The observation made from Fig. 9 suggests that PV more than 2.3 kW capacity will be uneconomical to fulfill the zero export operational goal.

As it is assumed that every day at 6:00 am the storage should be in 20% charge, high PV capacity would likely give surplus energy which cannot be consumed and will be wasted. Fig. 10 shows these renewable energy losses as a function of PV capacity. As shown in this figure when the PV capacity is more than 4 kW, there is renewable energy which cannot be consumed in the building and cannot be exported to the grid. As a result, this surplus energy will be wasted.

There are two sensitivity analyses for this operational goal. Fig. 11 shows the sensitivity of the total annual cost of the building to the government installation incentive rate. It can be seen that this incentive has a considerable effect on the optimal sizing of the PV and storage. For example, an installation incentive rate of 0.5 results in an optimal PV sizing of 4.3 kW which is nearly two times more than that when the incentive rate is 0.4. Fig. 12 shows the second sensitivity analysis, the annual cost to self-consumption incentive rate. This parameter has also considerable effect on the total cost and sizing of components. As shown in Fig. 12, a self-consumption incentive rate of 0.5 \$/kWh results in an optimal PV sizing of 4.7 kW.

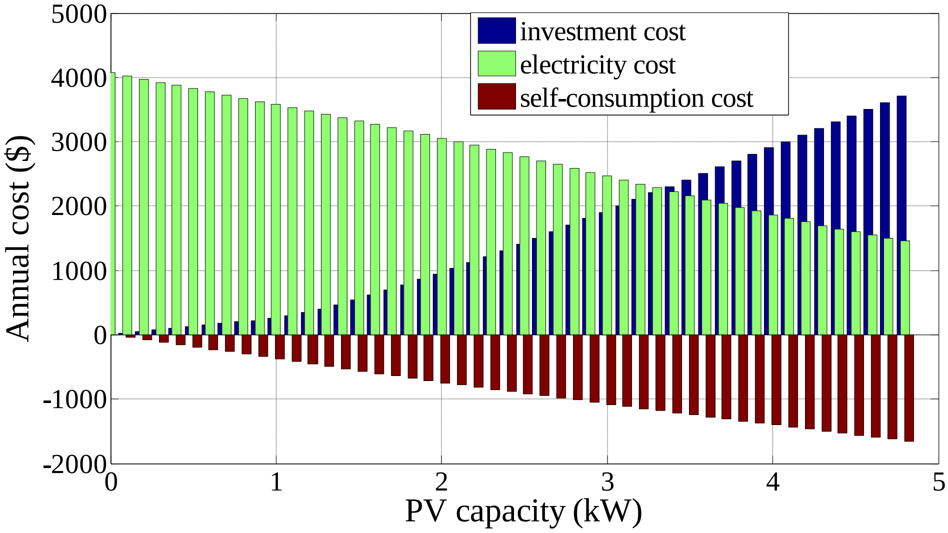


FIG. 8 COST STRUCTURE FOR DIFFERENT PV CAPACITY

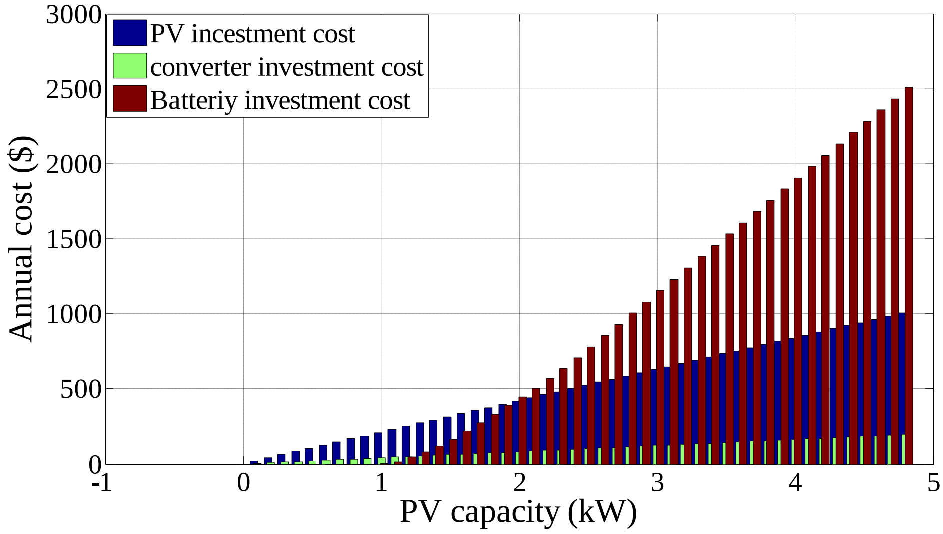


FIG. 9 DIFFERENT PARTS OF THE INVESTMENT COST

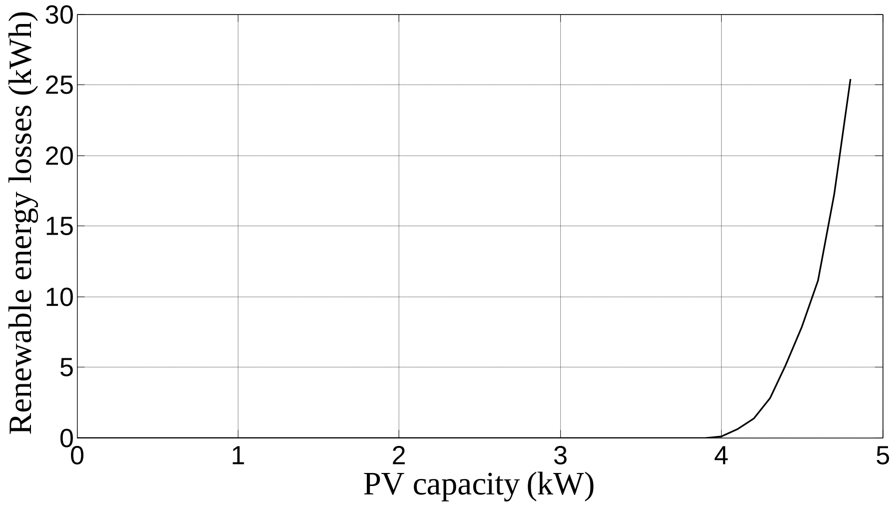


FIG. 10 ANNUAL RENEWABLE ENERGY LOSSES

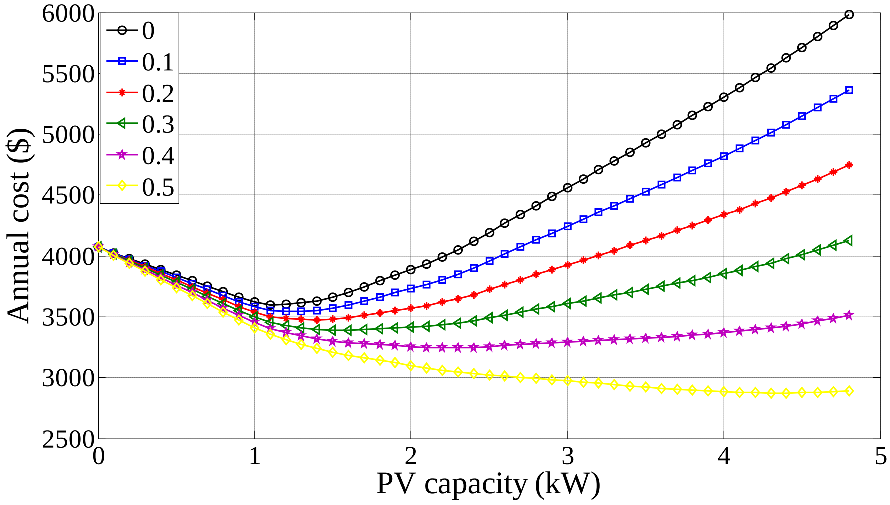


FIG. 11 TOTAL ANNUAL COST FOR DIFFERENT INSTALLATION INCENTIVE RATES

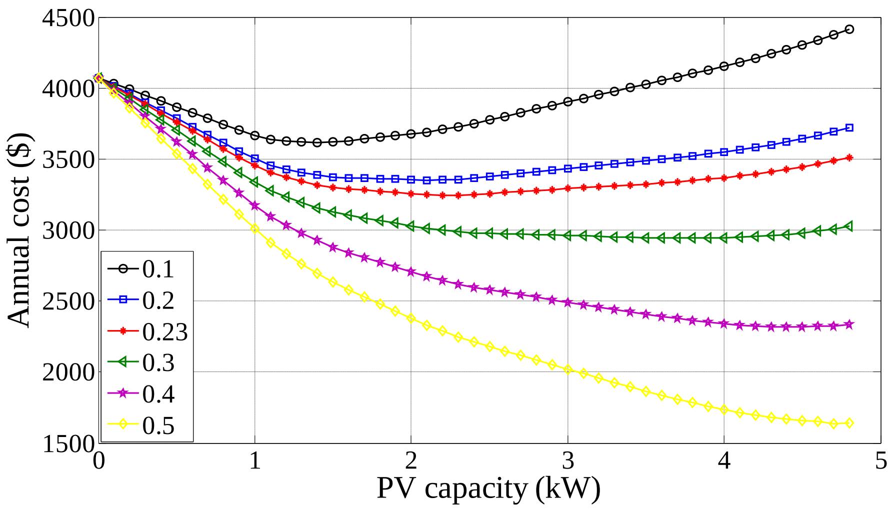


FIG. 12 TOTAL ANNUAL COST FOR DIFFERENT SELF-CONSUMPTION INCENTIVE RATES

Maximum Power Export

In this case, it is supposed that the building has the right to inject power with maximum level of 1.5 kW. Fig. 13 shows the required storage sizing as PV capacity increases. Storage is required for any PV

capacity greater than 2.6 kW to fulfill the operational goal of maximum power export of 1.5 kW. The storage sizing increases considerably, as an example, for a PV capacity of 4.8 kW, storage of 9.5 kWh is needed.

TABLE IV OPTIMAL PLAN (MAXIMUM POWER EXPORT)

P_{PV} (kW)	2.9
$E_{storage}$ (kWh)	0.5
CP_{inv} (\$)	775.6409
CP_{elec} (\$)	2966.1
$CR_{feed\text{-}in\text{-}tariff}$ (\$)	437.8151
$CR_{self\text{-}consumption}$ (\$)	0
CP_{CCL} (\$)	0
C_{total} (\$)	3245.1

The optimal PV and storage sizing for this operational goal and its cost parameters is shown in Table IV.

The important parameter in this operational goal is the maximum power export limit which can be different considering the location of building in the grid. Fig. 14 shows the sensitivity of the total annual cost to the power export limit. It can be seen that for any injected power less than its first limit (0.5 kW) all strategies will have the same annual cost. However, annual cost starts to increase for different power export limits, considering storage required to prevent the limit violation.

In addition, the sensitivity of required storage sizing to the maximum power limit has been shown in Fig. 15. It can be seen that the more the injection right is, the less storage sizing it is needed for the building to fulfill the operational goal.

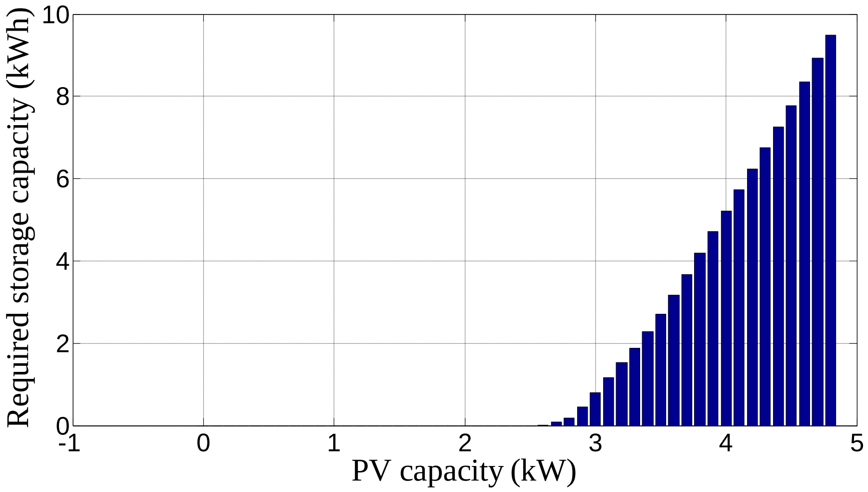


FIG. 13 REQUIRED STORAGE SIZING AS A FUNCTION OF PV CAPACITY

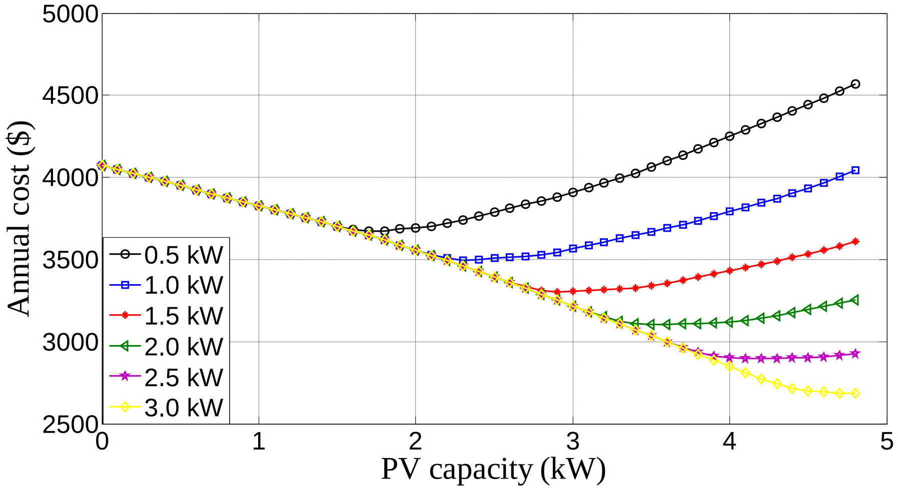


FIG. 14 SENSITIVITY OF TOTAL ANNUAL COST TO THE MAXIMUM POWER EXPORT LIMIT

Maximum Power Import

In this case, it is assumed that the maximum power that can be imported from the network is 2 kW. If the power consumed from the grid is more than the limit, the customer pays a CCL rate of 0.43 \$/kWh plus the price of power in that period. Assuming no limit for power injection, the plan with maximum PV rating is the most economical, which in this study is shown in Table V.

TABLE V OPTIMAL PLAN (MAXIMUM POWER IMPORT)

P_{PV} (kW)	4.8
$E_{storage}$ (kWh)	3.2
CP_{inv} ($)	1552.2
CP_{elec} ($)	805
$CR_{feed\text{-}in\text{-}tariff}$ ($)	696.9445
$CR_{self\text{-}consumption}$ ($)	0
CP_{CCL}($)	4.8563
C_{total} ($)	1665.1

Maximum Power Import and Export

Finally, it is assumed that the maximum power that can be imported from network is 2 kW, and the maximum power of 1.5 kW can be injected to network. The policy of CCL is applied for this case with excess consumption of 2 kW. As shown in Table VI, the optimal plan would have the PV sizing of 3.6 kW and storage sizing of 3.2 kWh.

Fig. 16 shows the required storage sizing for different PV capacity to fulfill this operational goal. It can be observed that there is a need of a minimum storage of 3.2 kWh to fulfill the maximum power import limit for all PV capacity. However, for PV capacity of 3.7 kW or greater, this storage sizing cannot fulfill this operational goal and need to be increased as shown in Fig. 16.

TABLE VI OPTIMAL PLAN (MAXIMUM POWER IMPORT AND EXPORT)

P_{PV} (kW)	3.6
$E_{storage}$ (kWh)	3.2
CP_{inv} ($)	1255.4
CP_{elec} ($)	958.5301
$CR_{feed\text{-}in\text{-}tariff}$ ($)	367.6020
$CR_{self\text{-}consumption}$ ($)	0
CP_{CCL}($)	7.3679
C_{total} ($)	1853.7

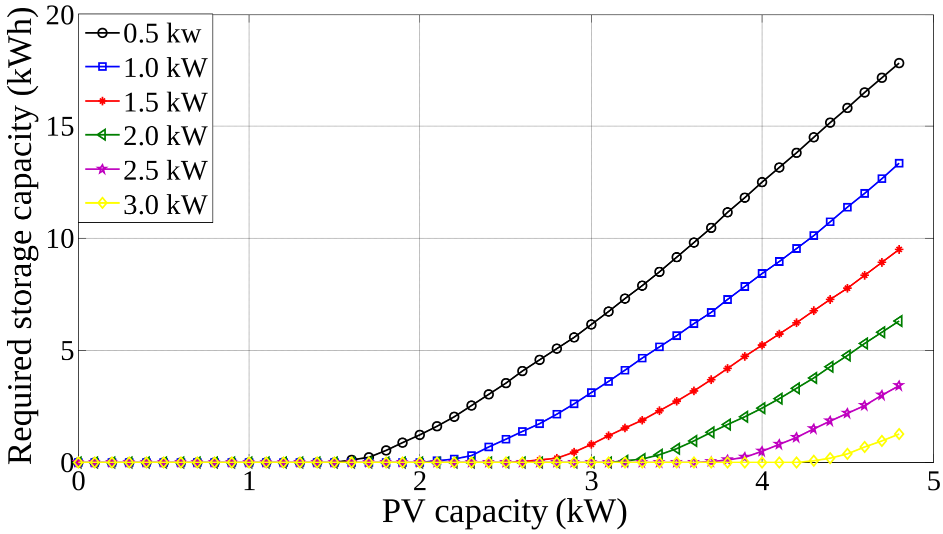


FIG. 15 SENSITIVITY OF REQUIRED STORAGE CAPACITY TO MAXIMUM POWER EXPORT LIMIT

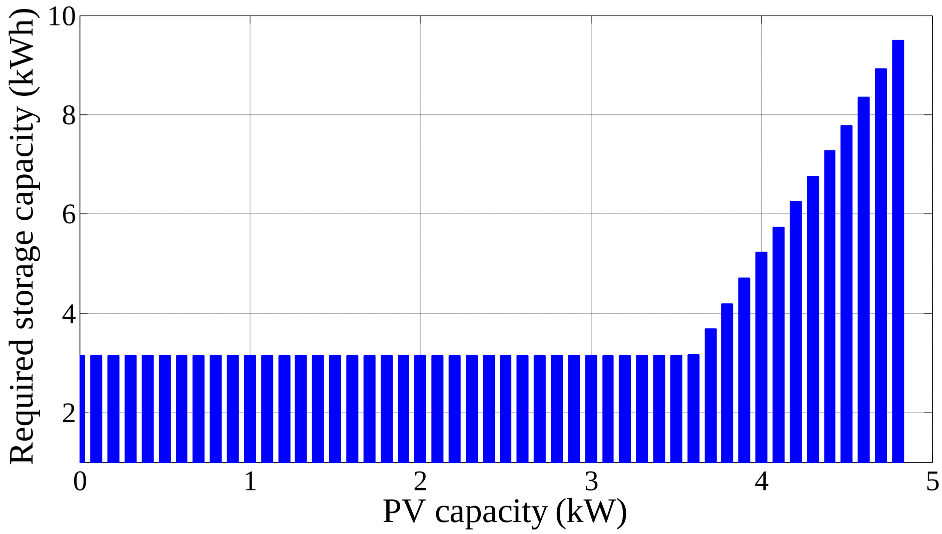


FIG. 16 STORAGE SIZING AS A FUNCTION OF PV CAPACITY

Conclusions

This paper provided a systematic algorithm to find out the optimal sizing of combined PV-energy storage for future grid-connected residential building. It was shown that the sizing of the resources is not self-determine and will depend on many cost and operational parameters. Five possible operational goals for future residential houses have been introduced. A residential building example was used to apply and examine the method for different operational goals. It was concluded that the optimal sizing of PV and energy storage is dependent on load profile and operational goal of residential building.

REFERENCES

Borowy, B.S., Salameh, Z.M., Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system, Energy Conversion, IEEE Transactions on, 11 (2) (1996) 367-375.

Bruno, S., Lamonaca, S., La Scala, M., Rotondo, G., Stecchi, U., Load control through smart-metering on distribution networks, in: PowerTech, 2009 IEEE Bucharest, 2009, pp. 1-8.

Castillo-Cagigal, M., Caamaño-Martín, E., Matallanas, E., Masa-Bote, D., Gutiérrez, A., Monasterio-Huelin, F., Jiménez-Leube, J., PV self-consumption optimization with storage and Active DSM for the residential sector, Solar Energy, 85 (9) (2011) 2338-2348.

Castillo-Cagigal, M., Gutiérrez, A., Monasterio-Huelin, F., Caamaño-Martín, E., Masa, D., Jiménez-Leube, J., A semi-distributed electric demand-side management system with PV generation for self-consumption enhancement, Energy Conversion and Management, 52 (7) (2011) 2659-2666.

Chen, S.X., Gooi, H.B., Scheduling of energy storage in a grid-connected PV/battery system via SIMPLORER, in: TENCON 2009 - 2009 IEEE Region 10 Conference, 2009, pp. 1-5.

Chiang, S.J., Chang, K.T., Yen, C.Y., Residential photovoltaic energy storage system, Industrial Electronics, IEEE Transactions on, 45 (3) (1998) 385-394.

Diaf, S., Diaf, D., Belhamel, M., Haddadi, M., Louche, A., A methodology for optimal sizing of autonomous hybrid PV/wind system, Energy Policy, 35 (11) (2007) 5708-5718.

Dufo-López, R., Bernal-Agustín, J.L., Yusta-Loyo, J.M., Domínguez-Navarro, J.A., Ramírez-Rosado, I.J., Lujano, Aso, J., I., Multi-objective optimization minimizing cost and life cycle emissions of stand-alone PV–wind–diesel systems with batteries storage, Applied Energy, 88 (11) (2011) 4033-4041.

Ekren, O., Ekren, B.Y., Ozerdem, B., Break-even analysis and size optimization of a PV/wind hybrid energy conversion system with battery storage – A case study, Applied Energy, 86 (7–8) (2009) 1043-1054.

Ekren, O., Ekren, B.Y., Size optimization of a PV/wind hybrid energy conversion system with battery storage using simulated annealing, Applied Energy, 87 (2) (2010) 592-598.

Hammons, T.J., Integrating Renewable Energy Sources into European Grids, in: Universities Power Engineering Conference, 2006. UPEC '06. Proceedings of the 41st International, 2006, pp. 142-151.

Hernández, J.C., Medina, A., Jurado, F., Optimal allocation and sizing for profitability and voltage enhancement of PV systems on feeders, Renewable Energy, 32 (10) (2007) 1768-1789.

Jayasekara, N., Wolfs, P., Analysis of power quality impact of high penetration PV in residential feeders, in: Universities Power Engineering Conference (AUPEC), 2010 20th Australasian, 2010, pp. 1-8.

Kaldellis, J.K., Zafirakis, D., Kavadias, K., Kondili, E., An Optimum Sizing Methodology for Combined Photovoltaic-Energy Storage Electricity Generation Configurations, Journal of Solar Energy Engineering-Transactions of the Asme, 131 (2) (2009).

Kellogg, W.D., Nehrir, M.H., Venkataramanan, G., Gerez, V., Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems, Energy Conversion, IEEE Transactions on, 13 (1) (1998) 70-75.

Koutroulis, E., Kolokotsa,D., Potirakis, A., Kalaitzakis, K., Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms, Solar Energy, 80 (9) (2006) 1072-1088.

Mulder, G., Ridder, F.D., Six, D., Electricity storage for grid-connected household dwellings with PV panels, Solar Energy, 84 (7) (2010) 1284-1293.

Nelson, D.B., Nehrir, M.H., Wang, C., Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems, Renewable Energy, 31 (10) (2006) 1641-

1656.

Oudalov, A., Cherkaoui, R., Beguin, A., Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application, in: Power Tech, 2007 IEEE Lausanne, 2007, pp. 621-625.

Riffonneau, Y., Bacha, S., Barruel, F., Ploix, S., Optimal Power Flow Management for Grid Connected PV Systems With Batteries, Sustainable Energy, IEEE Transactions on, 2 (3) (2011) 309-320.

Tan, C.W., Green, T.C., Hernandez-Aramburo, C.A., A stochastic method for battery sizing with uninterruptible-power and demand shift capabilities in PV (photovoltaic) systems, Energy, 35 (12) (2010) 5082-5092.

Tsengenes, G., Adamidis, G., Investigation of the behavior of a three phase grid-connected photovoltaic system to control active and reactive power, Electric Power Systems Research, 81 (1) (2011) 177-184.

Tonkoski, R., Lopes, L.A.C., El-Fouly, T.H.M., Coordinated Active Power Curtailment of Grid Connected PV Inverters for Overvoltage Prevention, Sustainable Energy, IEEE Transactions on, 2 (2) (2011) 139-147.